

# TinyDB: In-Network Query Processing in TinyOS

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# TinyDB: In-Network Query Processing in TinyOS

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# 1 Introduction

TinyDB is a query processing system for extracting information from a network of TinyOS sensors. Unlike existing solutions for data processing in TinyOS, TinyDB does not require you to write embedded C code for sensors. Instead, TinyDB provides a simple, SQL-like interface to specify the data you want to extract, along with additional parameters, like the rate at which data should be refreshed – much as you would pose queries against a traditional database. Given a query specifying your data interests, TinyDB collects that data from motes in the environment, filters it, aggregates it together, and routes it out to a PC. TinyDB does this via power-efficient in-network processing algorithms.

To use TinyDB, you install its TinyOS components onto each mote in your sensor network. TinyDB provides a simple Java API for writing PC applications that query and extract data from the network; it also comes with a simple graphical query-builder and result display that uses the API.

The primary goal of TinyDB is to make your life as a programmer significantly easier, and allow data-driven applications to be developed and deployed *much* more quickly than what is currently possible. TinyDB frees you from the burden of writing low-level code for sensor devices, including the (very tricky) sensor network interfaces. Some of the features of TinyDB include:

- *Metadata Management:* TinyDB provides a metadata catalog to describe the kinds of sensor readings that are available in the sensor network.
- *High Level Queries:* TinyDB uses a *declarative* query language that lets you describe the data you want, without requiring you to say how to get it. This makes it easier for you to write applications, and helps guarantee that your applications continue to run efficiently as the sensor network changes.
- *Network Topology:* TinyDB manages the underlying radio network by tracking neighbors, maintaining routing tables, and ensuring that every mote in the network can efficiently and (relatively) reliably deliver its data to the user.
- *Multiple Queries:* TinyDB allows multiple queries to be run on the same set of motes at the same time. Queries can have different sample rates and access different sensor types, and TinyDB efficiently shares work between queries when possible.
- *Incremental Deployment via Query Sharing:* To expand your TinyDB sensor network, you simply download the standard TinyDB code to new motes, and TinyDB does the rest. TinyDB motes share queries with each other: when a mote hears a network message for a query that it is not yet running, it automatically asks the sender of that data for a copy of the query, and begins running it. No programming or configuration of the new motes is required beyond installing TinyDB.

This document serves a number of purposes. The first sections are targeted at the sensor application programmer, and include a basic overview of the TinyDB system architecture, and a QuickStart guide to using the TinyDB system, its query language and APIs. The remaining sections are targeted at readers who want to extend the TinyDB system itself.

## 1.1 System Overview

This section provides a high level overview of the architecture of the TinyDB software. It is designed to be accessible to users of the TinyDB system who are not interested in the technical details of the system’s implementation. A detailed description of the TinyDB software design is reserved for Sections 4 and 5.

We begin with a short description of a typical use-case for TinyDB. Imagine that Mary wishes to locate an unused conference room in her sensor-equipped building, and that an application to perform this task has not already been built. The motes in Mary’s building have a sensor board with light sensors and microphones and have been programmed with a room number. Mary decides that her application should declare a room *in-use* when the average light reading of all the sensors in a room are above  $l$  and when the average volume is above  $v$ . Mary wants her application to refresh this occupancy information every 5 minutes. Without TinyDB, Mary would have to write several hundred lines of custom embedded C code to collect information from all the motes in a room, coordinate the communication of readings across sensors, aggregate these readings together to compute the average light and volume, and then forward that information from within the sensor network to the PC where the application is running. She would then have to download her compiled program to each of the motes in the room. Instead, if the motes in Mary’s building are running TinyDB, she can simply pose the following SQL query to identify the rooms that are currently in-use:

```
SELECT roomno, AVERAGE(light), AVERAGE(volume)
FROM sensors
GROUP BY roomno
HAVING AVERAGE(light) >  $l$  AND AVERAGE(volume) >  $v$ 
EPOCH DURATION 5min
```

TinyDB translates this query into an efficient execution plan which delivers the set of occupied rooms every 5 minutes. Mary simply inputs this query into a GUI – she writes no C code and is freed from concerns about how to install her code, how to propagate results across multiple network hops to the root of the network, how to power down sensors during the time when they are not collecting and reporting data, and many other difficulties associated with sensor-network programming.

We discuss the inner workings of TinyDB on such queries in Sections 4 and 5 below. In the remainder of this section, we present a high-level overview of the components of TinyDB. The system can be broadly classified into two subsystems:

1. Sensor Network Software: This is the heart of TinyDB, although most users of the system should never have to modify this code. It runs on each mote in the network, and consists of several major pieces:

- *Sensor Catalog and Schema Manager*: The catalog is responsible for tracking the set of *attributes*, or types of readings (e.g. light, sound, voltage) and properties (e.g. network parent, node ID) available on each sensor. In general, this list is not identical for each sensor: networks may consist of heterogeneous collections of devices, and may be able to report different properties. (See Section 5.1 for details.)

- *Query Processor*: The main component of TinyDB consists of a small query processor. The query processor uses the catalog to fetch the values of local attributes, receives sensor readings from neighboring nodes over the radio, combines and aggregates these values together, filters out undesired data, and outputs values to parents. (See Section 5.2 for details.)
  - *Memory Manager*: TinyDB extends TinyOS with a small, handle-based dynamic memory manager. (See Section 5.3 for details.)
  - *Network Topology Manager*: TinyDB manages the connectivity of motes in the network, to efficiently route data and query sub-results through the network. (See Section 5.4 for details.)
2. Java-based Client Interface: A network of TinyDB motes is accessed from a connected PC through the *TinyDB client interface*, which consists of a set of Java classes and applications. These classes are all stored in the `tinyos-1.x/tools/java/tinyos/tinydb` package in the source tree. The specific classes are described in Section 4; major classes include:
- A network interface class that allows applications to inject queries and listen for results (Section 4.1.1)
  - Classes to build and transmit queries (Sections 4.1.3, 4.1.5, 4.1.6)
  - A class to receive and parse query results (Section 4.1.4)
  - A class to extract information about the attributes and capabilities of devices (Section 4.1.7)
  - A GUI to construct queries (Sections 4.2.3, 4.2.4)
  - A graph and table GUI to display individual sensor results (Sections 4.2.5, 4.2.6, 4.2.7)
  - A GUI to visualize dynamic network topologies (Section 4.2.8)
  - An application that uses queries as an interface on top of a network of sensors (Section 4.2)

## 2 Quick Start: Running Queries with TinyDB

In this section, you will learn how to install TinyDB software, set up a network of TinyDB motes, inject a query into the network, and collect the results of the query.

### 2.1 Installation and Requirements

TinyDB requires a basic TinyOS installation, with a working Java installation (and `javax.comm` library). It is currently designed to work with the nesC compiler (next generation C-like language for TinyOS) and `avr-gcc 3.1`. To obtain these tools, download the TinyOS 1.0 release from

<http://webs.cs.berkeley.edu/tos>

Click on the link for your platform (PC Linux or Windows), and follow the installation instructions.

The most recent version of TinyDB is always available from the TinyOS SourceForge repository; see the TinyOS CVS Page for instructions on using CVS. In addition to the standard TinyOS distribution,

TinyDB includes a number of additional files detailed in Appendix A of this document. The following table summarizes the software requirements of TinyDB:

Required Software	Notes
avr-gcc	Version 3.1 or later
Java SDK	Version 1.3 or later
nesC compiler	From the TinyOS alpha release
javax.comm tools	Version 1.3 or later, from IBM
TinyOS	From SourceForge CVS

To verify that your installation is working properly, do the following:

1. Compile and install TinyDB on the mote. To do this, connect the mote to the programming board, then type the following:

- `cd tinyos-1.x/apps/TinyDBApp/`
- `make mica`
- `make mica install`

If this fails, verify that your installation works (see the instructions on the web site), and that you have all of the TinyDB files listed above.

2. Compile and run the TinyDBMain java classes. To do this, type the following:

- `cd tinyos-1.x/tools/java/net/tinyos/tinydb`
- `make`
- `cd tinyos-1.x/tools/java`
- `java net/tinyos/tinydb.TinyDBMain`

You'll need to make sure you have the following jar files in your classpath (they should all be available in `tinyos-1.x/tools/java/jars`):

- `JLex.jar`
- `cup.jar`
- `plot.jar`

You must also have the `tinyos-1.x/tools/java` directory in your classpath.

If you wish to take advantage of TinyDB's compatibility with the PostgreSQL database system, you'll need to install and configure Postgres (see Section 6) and include the `pgjdbc2.jar` file in your classpath.

Your `CLASSPATH` should now look something like this:

```
./path/to/java/jre/lib/rt.jar:/path/to/java/lib/dt.jar:  
/path/to/java/lib/tools.jar:/opt/IBMJava2-13/jre/lib/ext/comm.jar:  
tinyos-1.x/tools/java/jars/plot.jar:tinyos-1.x/tools/java/jars/cup.jar:  
tinyos-1.x/tools/java/jars/JLex.jar:tinyos-1.x/tools/java
```



You may see warnings about “deprecated classes” when `javac` runs. These are OK, and you can ignore them. After running the java command, you should see the TinyDB control panel and query interface appear.

Once you have a working installation of these files, continue on to the next section to learn how to run queries with TinyDB.

## 2.2 Setting up a Network of TinyDB motes

The first step is to program a number of motes with the TinyDB software. Each of these motes must have a unique ID; recall that, in TinyOS, you can set the ID of a mote when running `make install` by appending `.nodeid` – for example, to program a TinyDB mote at ID 2, you would type:

- `cd tinyos-1.x/apps/TinyDBApp/`
- `make mica install.2`

To run TinyDB, you will need at least two motes: one to act as the basestation mote, and one or more to distribute and run queries over. You may want to place a sticker on your chosen basestation mote, since you will need to identify it visually. All motes, including the basestation, run the same TinyDBApp application, however, *the basestation mote must be set to ID 0*.

After programming your motes, connect the programming board to your computer via the serial port, and place the basestation mote in the programming board. Turn on all of the motes.

Figure 1 illustrates the basic setup of motes and PC.

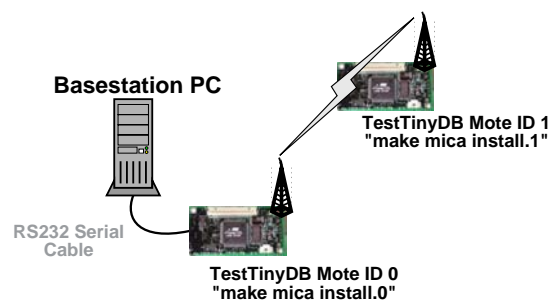


Figure 1: Two TinyDB motes set up to run a query.

## 2.3 Running the TinyDBMain GUI

The TinyDBMain Java application provides a graphical interface for distributing queries over motes and collecting data from them. To run this application, type:

- `cd tinyos-1.x/tools/java/net/tinyos/tinydb`
- `make`
- `cd tinyos-1.x/tools/java`

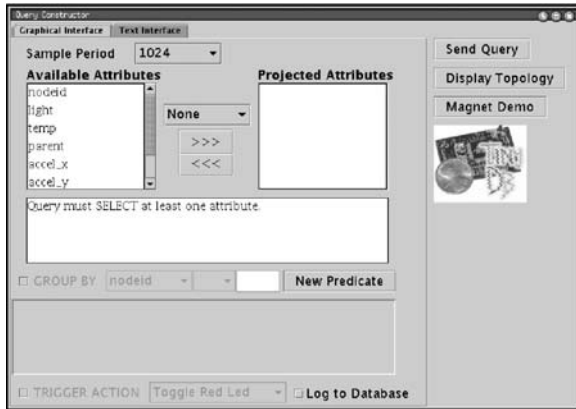


Figure 2: Query Window



Figure 3: Command Window

- `java net.tinyos.tinydb.TinyDBMain`

Two windows should appear; one, the *command* window (Figure 3), allows you to send a variety of control commands to the motes. The other, the *query* window (Figure 2), allows you to build and send queries into the network. We will be focusing on the operation of the query window in the next section; the command window is fairly self-explanatory.

The query window contains a **Display Topology** button to show the network topology. This button actually generates a particular query that is executed by the motes, with results displayed in a special visualization. It is a good idea to display you network topology and make sure that all your motes are alive and communicating.

Once you see that your network of motes is operational, you can proceed to constructing queries.

**TIP:** If you have difficulty sending queries into the network, verify that your AM group ID is set the same in TinyOS and in the TinyDB Java client. In TinyOS, the AM group is set in `tinyos-1.x/tos/system/AM.h` in the variable `TOS_AM_GROUP`. In TinyDB, the AM group is set via the config file variable `am-group-id` which is stored in `tinyos-1.x/tools/java/tinydb.conf`; see Section 3.5 for more information.

### 3 Using TinyDB

TinyDB provides a high-level, *declarative* language for specifying queries. In a declarative language you describe *what* you want, but not *how* to get it. Declarative languages are advantageous for two reasons. First, they are relatively easy to learn, with queries that are easy to read and understand. Second, they allow the underlying system to change how it runs a query, without requiring the query itself to be changed. This is important in a volatile context like sensor networks, where the best underlying implementation may need to change frequently – e.g. when motes move, join or leave the network, or experience shifting radio interference. In TinyDB, the execution strategy for a user query can change each time the query is run, or even *while* the query runs, without any need for re-typing the query or recompiling an application that embeds the query.

Before describing TinyDB’s query facilities, a few words on TinyDB’s data model are in order. TinyDB implicitly queries one single, infinitely-long logical table called **sensors**. This table has one column for each attribute in the catalog, including sensor attributes, nodeIDs, and some additional “introspective” attributes (properties) that describe a mote’s state. This table conceptually contains one row for each reading generated by any mote, and hence the table can be thought of streaming infinitely over time. A given mote may not be able to generate all the attributes, e.g., if it does not have the sensor that generates the attribute. In that case, the mote will always generate a NULL value for that attribute.

TinyDB’s query language is based on SQL, and we will refer to it as TinySQL. As in SQL, queries in TinySQL consist of a set of attributes to select (e.g. light, temperature), a set of *aggregation expressions* for forming aggregate result columns, a set of *selection predicates* for filtering rows, and optionally a grouping expression for partitioning the data before aggregation. Aggregation is commonly used in the sensor environment.

Currently, TinySQL results are very similar to SQL, in that they are based on snapshots in time – that is, they are posed over rows generated by multiple sensors at one point in time. *Temporal* queries that combine readings over several time periods are not supported in the current release. Instead, TinySQL runs each query repeatedly, once per time-period or “epoch”. The duration of an epoch can be specified as part of a TinySQL query; the longer the duration, the less frequent the results, and the less drain on the mote batteries.

### 3.1 The Query Window

The query window provides a graphical interface for building queries. As you use the widgets in the window, query text is dynamically constructed in the text box in the middle of the screen. This box is also used for error messages.

**TIP:** The current query text can always be refreshed by clicking on a column in the **Available Attributes** list.

The topmost widget in the window is the **Epoch Duration** widget, which specifies the interval at which the query is re-evaluated. We recommend that the epoch duration be set as large as possible to minimize power drain on the motes.

To specify the query to run each epoch, you first choose the attributes and/or aggregate expressions to appear in the output. Attributes are specified by choosing them in the **Available Attributes** list, and pressing the “>>>” button so that they appear in the **Projected Attributes** list. Optionally, attributes may be placed in simple *aggregate expressions* by choosing an aggregate from the pull-down menu in the middle of the screen (default: **None**). At this stage, the Projected Attributes list must contain either all aggregate expressions, or all attributes; a mixture will result in an error message unless there is a GROUP BY clause. We will return to this point shortly.

To select only some of the rows to be considered in the query, you can specify predicates to filter the data, via the **New Predicate** button at the bottom of the screen. All the predicates you select will be implicitly “AND”ed together. “OR” is not yet supported.

If you used aggregate expressions in your **Projected Attributes** list, you can also specify a

GROUP BY column by clicking on the **GROUP BY** checkbox and selecting from the pulldown menu. The pulldown menu to the right of the GROUP BY column is for right-shifting the (binary) value of the column before grouping; each shift divides the value of the GROUP BY column by 2. This has the effect of reducing the number of possible groups: the more times you divide by 2, the fewer possible groups there can be.

After adding a GROUP BY column, you can now add it (unaggregated!) to the **Projected Attributes** by selecting it from the **Available Attributes** list and pressing the “>>>” button. This is the only way to mix aggregates and attributes in your query output<sup>1</sup>.

### 3.1.1 Triggers

TinyDB includes a facility for simple *triggers*, or queries that execute some command when a result is produced. Currently, triggers can be executed only in response to some local sensor reading that satisfies the conditions specified in the **WHERE** clause of the query. *Aggregate queries cannot have triggers associated with them.* Whenever a query result satisfies the **WHERE** clause of a query, the *trigger action* is executed. This action is a named command stored in the schema of the mote (see Section 5.1.1 for more information.)

The current TinyDB interface includes simple trigger actions for blinking LEDs and sounding the sounder (the small speaker on the Mica sensor board.) A trigger action can be specified via the GUI by clicking the **TRIGGER ACTION** checkbox and selecting the appropriate action. Other actions can be specified via the textual interface (see the next section) and the schema API (described in Section 5.1.1.)

As an example of what triggers can be used for, consider an application where the user wants to sound an alarm whenever the temperature near a sensor goes above some threshold. This can be accomplished via the simple trigger query:

```
SELECT temp
FROM sensors
WHERE temp > thresh
TRIGGER ACTION SetSnd(512)
EPOCH DURATION 512
```

The **SetSnd** command sounds the sounder, and the value of 512 specifies a sound duration of 512 ms.

---

<sup>1</sup>Note that this restriction also exists in SQL, and is implicit in the meaning of aggregation. The only non-aggregated attributes that are meaningful in the **SELECT** list are attributes that appear in the **GROUP BY** list. As an example, consider a query with *no* **GROUP BY** attributes. It can only produce one output row per epoch, which contains aggregate values computed from all the input rows. It is not meaningful to ask for a raw attribute in the output of such a query – there can be multiple values for each attribute in the input, so there is no well-specified unique value to place in the single output column. The same restriction applies in a **GROUP BY** query, with the exception of the columns in the **GROUP BY** expression – these columns are guaranteed to have a single unique value per group, and hence can appear alongside aggregate expressions.

## 3.2 Composing Your Own TinyDB Queries

When using TinyDB, it is also possible to write queries by hand, either by using the “Text Interface” pane of the GUI (which can be brought up by default by using the command-line argument “-text”), or via the `SensorQueryer.translateQuery` API call. We assume here that the reader has a familiarity with the basics of SQL. A number of books and websites provide simple SQL tutorials. No deep knowledge of SQL is required to use TinyDB; the basics will do. The simplest way to learn TinySQL is to use the graphical query builder described in Section 3.1. However, we also provide a simple, informal description of the syntax here.

TinyDB provides an SQL-like query language, which is simplified in a number of ways, but which also provides some new sensor-specific syntax. TinySQL queries all have the form:

```
SELECT select-list
[FROM sensors]
WHERE where-clause
[GROUP BY gb-list
[HAVING having-list]]
[TRIGGER ACTION command-name[(param)]]
[EPOCH DURATION integer]
```

The **SELECT**, **WHERE**, **GROUP BY** and **HAVING** clauses are very similar to the functionality of SQL. Arithmetic expressions are supported in each of these clauses. As in standard SQL, the **GROUP BY** clause is optional, and if **GROUP BY** is included the **HAVING** clause may also be used optionally.

## 3.3 TinySQL vs. Standard SQL

### Limitations

- The **FROM** clause must always list exactly one table, entitled **sensors**. The **FROM** clause is also optional.
- In the current version the **WHERE** and **HAVING** clauses can contain only simple conjunctions over arithmetic comparison operators. There is no support for the Boolean operators **OR** and **NOT**, or string matching comparisons (SQL’s **LIKE** and **SIMILAR** constructs).
- There is currently no support for sub-**SELECT**s (subqueries).
- There is currently no support for column renaming (SQL’s **AS** construct) in the *gb-list*.
- Arithmetic expressions are currently limited to the form *column op constant*, where *op* is one of {+, −, \*, /}.

### Sensor-Specific Features

The **TRIGGER ACTION** clause specifies an (optional) trigger action that should be executed whenever a query result is produced. See Section 3.1.1 for more information about triggers. The command name

Option	Description	Possible Values	Default
show-command-window	Should the command window (see Figure 3) be shown?	true, false	true
am-group-id	The AM group with which TinyDB motes have been programmed	0-255	125
default-query	The default query to show in the TinyDB text command window	Any string	none
postgres-user	The name of the Postgres user (see Section 6 below)	Any string	none
postgres-passwd	The password (if any) for the specified user	Any string	none
postgres-db	The name of database where TinyDB results should be logged	Any string	none
postgres-host	The IP-address or hostname of a TCP-enabled Postgres server	A valid IP address	none
start-sf	Should TinyDB automatically start a serial forwarder?	true, false	true
sf-host	The hostname of the serial forwarder to contact (if start-sf is false)	A valid IP address	localhost
sf-port	The port the serial forwarder is running on	1-65535	9000

Table 1: Config file options and default values

must be a command registered with the **COMMAND** component (see Section 5.1.1.) An optional integer parameter may be passed to the command.

The time between epochs is specified in the query via the **EPOCH DURATION** clause. The units for this duration are specified in milliseconds. If no epoch duration is specified, a value of 1024 ms is used by default.

### 3.4 The Command Line

TinyDB provides a few simple command line options, as follows:

- **-text**: Start the GUI in the text panel.
- **-gui**: Start the GUI in the graphical query input window (default.)
- **-cmdwindow**: Display the command window (overrides the config file (see Section 3.5) setting.)
- **-configfile *filename***: Loads the config file from *filename*.
- **-run “*query*”** : Executes the specified query in text-mode (see Section 3.6.)
- **-debug**: Enable debugging messages (causes lots of messages to be printed on the command line.

### 3.5 The Config File

TinyDB uses a configuration file to configure some of its settings; this file is called “tinydb.conf” in the `tinyos-1.x/tools/java/tinyos/tinydb` directory. This file consists of colon (“:”) delimited pairs of settings and values. Blank lines and comments beginning with “%” are also allowed. Table 1 summarizes the major configuration file options. The configuration file is read once when the TinyDB application starts.

Settings in the configuration file are available to TinyDB java components via static methods in the `Config.java` class. `Config.init(...)` is called when `TinyDBMain` is instantiated. Components can call `Config.getParam(...)` to retrieve the value of a setting; if the setting has no value, `null` is returned.

### 3.6 Text Mode

TinyDB provides a very simple text mode for running queries (when using the `-run` command line option.) Query results are printed out to the console ; notes are reset each time a new query is posed (no interface to stop a currently running query or run multiple queries is currently available via this interface.)

For example, posing the command (in a single mote network):

```
java net.tinyos.tinydb.TinyDBMain -run ‘select nodeid,light epoch duration 1024’
```

produces output resembling:

Epoch	nodeid	light
3	12	860
4	12	860
5	12	861
8	12	860
9	12	879
11	12	860
12	12	860
...		

### 3.7 The LEDS

The LEDS on TinyDB motes are used to indicate the current status of the device; each LED is used to communicate one of several pieces of information, depending on the current status of the mote. A simple selection query should cause the mote to blink its yellow LED once per epoch, and its red LED once per data value forwarded up the tree. The following table summarizes other LED actions by mote status:

Mote Status	LED Response	Notes
Sent Message	Red Toggle	Once per query
Received Aggregate From Child	Green Toggle	
End of Epoch	Yellow Toggle	
Aborted Query	All LEDS On	
Reset Mote	All LEDS Flash	

## 4 Developing For TinyDB: Java API

Up to this point, we have described how to use TinyDB from the provided GUI. However, developers will want to embed TinySQL queries and fetch TinyDB result rows from within application programs.

TinyDB provides a Java API for building such programs, which we describe here. The provided GUI application is a good example of the use of the API, so we describe it here as well.

We begin with an overview of the API, and go on to an overview of the GUI program, which exercises the API. The discussion here is fairly high level, and is intended to accompany some investigation of the code itself.

## 4.1 The TinyDB Java API

The API contains a number of objects encapsulating the TinyDB network, the TinyDB catalog, the construction of TinyDB queries, and the manner in which the application listens for and interprets query results. These objects appear in the corresponding `.java` files in `tinyos-1.x/tools/java/tinyos/tinydb`.

### 4.1.1 TinyDBNetwork

This object is the main interface to a network of motes. It is responsible for injecting new queries into the network (`sendQuery()`), for cancelling queries (`abortQuery()`), and for providing results from the network to multiple query “listeners”. Only one instance of the `TinyDBNetwork` object needs to be allocated for a network; that instance can manage multiple ongoing queries, and multiple listeners. Each query’s output can be sent to multiple listeners, and each listener can listen either to a single query, or to all queries.

Internally, the object maintains a list of live queries, and three sets of listeners:

1. `processedListeners` are signed up for a specific query ID, and get a stream of final (“processed”) answer tuples for that query.
2. `qidListeners` are signed up for a specific query ID, and get copies of all messages that arrive for that query. These messages may not be final query answers. They may be individual attributes from an answer tuple, or unaggregated sub-result tuples.
3. `listeners` are signed up to receive a copy of all unprocessed messages for *all* queries.

The various listeners can be added or deleted to the object on the fly via `addResultListener()` and `removeResultListener()` – note that different arguments to the `addResultListener` method result in one of the 3 different kinds of listeners above.

The `TinyDBNetwork` object handles all incoming AM messages from the serial port, and dispatches copies of them to the `listeners` and `qidListeners` accordingly. It also processes the messages to generate result tuples (via `QueryResult.MergeQueryResult()`) and sends them to `processedListeners` accordingly. As part of processing results, it maintains info on epochs to make sure that the epoch semantics of the results are correct.

Internally, the `TinyDBNetwork` object also has a background thread that participates in the sensor network’s routing algorithms. It periodically sends information down the routing tree, so that children know to choose the root as a parent, and so that children can decide how to share the timeslots in an epoch.



#### 4.1.2 SensorQueryer

This class appears in the `parser` subdirectory. It represents a simple parser for TinySQL. The main method of interest is `translateQuery`, which takes an SQL string and returns a corresponding `TinyDBQuery` object, which we proceed to describe next.

#### 4.1.3 TinyDBQuery

This is a Java data structure representing a query running (or to be run) on a set of nodes.

Queries consist of:

- a list of attributes to select
- a list of expressions over those attributes, where an expression is
  - a filter that discards values that do not match a boolean expression
  - an aggregate that combines local values with values from neighbors, and optionally includes a GROUP BY column.
- an SQL string that should correspond to the expressions listed above.

In addition to allowing a query to be built, this class includes handy methods to generate specific radio messages for the query, which `TinyDBNetwork` can use to distribute the query over the network, or to abort the query.

It also includes a support routine for printing the query result schema.

#### 4.1.4 QueryResult

This object accepts a query result in the form of an array of bytes read off the network, parses the results based on a query specification, and provides a number of utility routines to read the values back. It also provides the `mergeQueryResult` functionality for `processedListeners`. This does concatenation of multiple aggs as separate attributes of a single result tuple, and finalizes aggregates, by combining data from multiple sensors.

#### 4.1.5 AggOp

This provides the code for the aggregation operators SUM, MIN, MAX, and AVERAGE. It includes representation issues (internal network codes for the various ops, and code for pretty-printing), and also the logic for performing final merges for each aggregate as part of `QueryResult:MergeQueryResult()`.

#### 4.1.6 SelOp

This provides the logic for selection predicates. Currently this includes representations for simple arithmetic comparisons (internal network codes for the arithmetic comparators, and pretty-printing.)

#### 4.1.7 Catalog

This object provides a very (very!) simple parser for a catalog file – it reads in the file, and after parsing it provides a list of attributes.

#### 4.1.8 CommandMsgs

This is a class with static functions to generate message arrays that can be used to invoke commands on TinyDB motes.

### 4.2 The TinyDB Demo Application

The TinyDB application allows users to interactively specify queries and see results. It also serves as an example of an application that uses the TinyDB API. As with traditional database systems, it is expected that many programmers will want to embed queries within more specialized application code. Such programmers can look at the TinyDB application for an example of how this is done.

The TinyDB application consists of only a few objects:

#### 4.2.1 TinyDBMain

This is the main loop for the application. It opens an *Active Message (AM)* connection to the Serial Port (“COM1”), and uses it to initialize a `TinyDBNetwork` object. It allocates the GUI objects `CmdFrame` and `QueryFrame` for the application, which issue queries and in turn generate visualizations of results. There are also some simple wrapper routines for the `TinyDBNetwork` methods to add and remove queries from listeners.

#### 4.2.2 CmdFrame

This is a simple GUI for sending TinyDB commands (from the `CommandMsgs` API object) into the network. See Figure 3.

#### 4.2.3 MainFrame

This is the main GUI for building queries with TinyDB, as shown in Figure 2. It provides a simple API for generating new query ID’s and processing keyboard input. The buttons along the right send either send the current query being built (“Send Query”) into the network for execution, or execute a predefined query, as follow:

1. **Display Topology:** A visualization of the network topology, which is extracted from the network via a standard TinyDB query.
2. **Mag. Demo:** A visualization of magnetometers laid out in a fixed  $x \times y$  grid. This is an example of simple demo application that can run on TinyDB: in this case, TinyDB is used to identify sensors with magnetometer readings greather than some threshold to detect metallic objects moving through a grid of motes.

The major portion of the GUI contains a tabbed pane that provides two different interfaces for inputting queries:

1. **GuiPanel**: A graphical query builder to construct a valid `TinyDBQuery` object and send it into the network via `TinyDBNetwork.sendQuery()` (Figure 2.) In addition to allowing users to specify ad hoc queries, it provides a button to send off two pre-prepared queries that have special visualizations:
2. **TextPanel**: A textual query editor that allows queries to be input in TinySQL language. See 3.2 for more information.

#### 4.2.4 QueryField

Simple support routines for handling attributes in the query builder.

#### 4.2.5 ResultFrame

`ResultFrame` displays a scrolling list with results from queries in it, side-by-side with a graph of query results when such results are available. For each query, it adds a `processedListener` to the `TinyDBNetwork` in order to receive the results, which it plots via `ResultGraph`.

#### 4.2.6 ResultGraph

A simple wrapper for the `plot` package, to interactively graph query results.

#### 4.2.7 plot

A graph-plotting package from the Ptolemy project. More information about the Ptolemy is available on the Ptolemy home page.

#### 4.2.8 topology

A set of classes for constructing the TinyDB network-topology-extraction query, and for displaying the results as a (dynamic) topology graph.

#### 4.2.9 MagnetFrame

`MagnetFrame` is a simple visualization to display an  $x \times y$  array that represent a grid of sensors and to darken circles representing sensors whose magnetometer readings go above some threshold. This was used for a demo that tracked the movement of a magnet mounted on a matchbox car.

`MagnetFrame` runs a simple query of the form

```
SELECT nodeid, mag_x FROM sensors WHERE mag_x > m EPOCH DURATION 256
```

## 5 Inside TinyDB

The prior discussion was been directed to TinyDB administrators, users, and application developers. This section is targeted at readers who are interested in extending or modifying the internals of the TinyDB code that runs on the motes.

We assume that the reader of this section is familiar with code development for the Berkeley motes in the TinyOS framework. For documentation and tutorials on TinyOS, please see the TinyOS web page.

In this section we discuss the TinyOS components that make up TinyDB. The component diagram for TinyDB – including the TinyOS components it references – is shown in Figure 4.

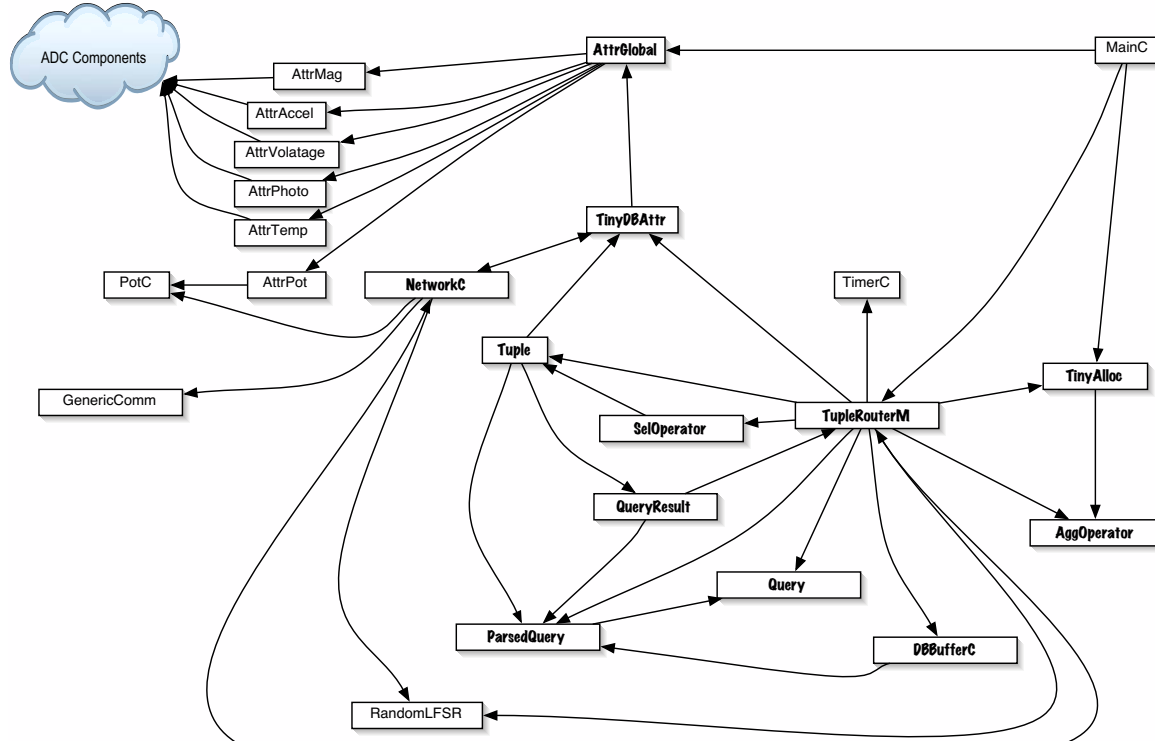


Figure 4: Component diagram. TinyDB-specific components are in the bold font.

### 5.1 The TinyDB Sensor Catalog and Schema Manager

A *schema* describes the capabilities of the motes in the system as a single virtual, database “table”. This table can contain any number of typed *attributes*. It can also contain handles to a set of *commands* that can be run within the query executor, much like “methods” in the Object-Relational extensions to SQL.

During query processing, sensor readings from each mote are placed into *tuples*, which may be passed between motes for multi-hop routing and/or aggregation, or which may be passed out the serial port at the top of the network to the front-end code.

### 5.1.1 Attr and Command

The `Attr` and `Command` components contain the code to manage the schema of the mote. The schema consists of tables of typed attributes and commands, and associated routines to update and query these tables.

The `Attr.nc` component implements the `AttrRegister.nc` and `AttrUse.nc` interfaces for getting and setting the values of attributes.

Schema commands can be invoked locally via (`CommandUse.invoke`), and to send a message to invoke schema commands on other nodes (`CommandUse.invokeMsg`), both of which are implemented by the `Command.nc` module.

See the *TinySchema* document for complete details on how to manage attributes and commands for TinyDB.

### 5.1.2 TinyDBAttr

This simple component is the hub for all the builtin attributes of TinyDB. It wires all the components that implement the builtin attributes together. This component must be updated if you add a new component that implements new attributes for TinyDB.

### 5.1.3 TinyDBCommand

This simple component is the hub for all the builtin commands of TinyDB. It wires all the components that implement the builtin commands together. This component must be updated if you add a new component that implements new commands for TinyDB.

### 5.1.4 Tuple

This component provides fairly straightforward utilities to manage the `Tuple` data structure, as defined in `TinyDB.h`.

### 5.1.5 QueryResult

This component converts between `Tuples`, `QueryResults`, and byte-strings. These data structures are all defined in `tinycos-1.x/tos/lib/TinyDB/TinyDB.h`. Briefly, a `Tuple` is a typed vector of values, as in SQL; a `QueryResult` holds a tuple and some metadata, including the query ID, an index into the result set, and an epoch number.

## 5.2 TinyDB Query Processing Operators

### 5.2.1 TupleRouter

This deceptively-named component provides the main query processing functionality on a mote. As Figure 4 makes clear, `TupleRouter` is at the heart of the TinyDB system. It is called a tuple “router” because it routes tuples through a variety of *local* query processing components. *This component*

*does not do network routing!* For information on network routing in TinyDB, see the component `NetworkC.nc` (Section 5.4).

The `TupleRouter` component contains three main execution paths:

- Handling of new query messages
- Result computation and propagation (each time a clock event goes off)
- Subtree result message handling

We discuss these in turn.

### Handling New Queries

New queries arrive in `TupleRouter` via the `Network.queryMsg` event. Each query is assumed to be identified by a globally unique ID, which must be generated by the Java front-end APIs. Query messages contain a part of a query: either a single field (attribute) to retrieve, a single selection predicate to apply, or a single aggregation function to apply. All the `QueryMessages` describing a single query must arrive before the router will begin routing tuples for that query.

Once all the `QueryMessages` have arrived, the router calls `parseQuery()` to generate a compact representation of the query in which field names have been replaced with field IDs that can be used as offsets into the sensors local catalog (`Schema`).

Given a `parsedQuery`, the tuple router allocates space at the end of the query to hold a single, “in-flight” tuple for that query – this tuple will be filled in with the appropriate data fields as the query executes.

`TupleRouter` then calls `setSampleRate()` to start (or restart) the mote’s 32khz clock to fire at the appropriate data-delivery rate for all of the queries currently in the system. If there is only one query, it will fire once per “epoch” – if there are multiple queries, it will fire at the greatest common divisor of the delivery intervals of all the queries.

### Tuple Delivery

Whenever a clock event occurs in `TupleRouter` (`Timer.fired`), the router must perform four actions:

1. Deliver tuples that were completed on the previous clock event (`deliverTuplesTask`). If the query contains an aggregate, deliver the aggregate data from the aggregate operator; if not, deliver the tuple that was filled out during the last iteration. Reset the counters that indicate when these queries should be fired again.
2. Decrement the counters for all queries. Any queries whose counters reach 0 need to have data delivered. Reset the expression-specific state for these queries (this is specific to the expressions in the queries – `MAX` aggregates, for instance, will want to reset the current maximum aggregate to some large negative number.)
3. Fetch data fields for each query firing this epoch. Loop through all fields of all queries, fetch them (using the `Schema` interface), and fill in the appropriate values in the tuples on the appropriate queries.

4. Route filled-in tuples to query operators. First route to selections, then the aggregate (if it exists).  
If any selection rejects a tuple, discard it.

### Neighbor Result Arrival

When a result arrives from a neighbor, the `TupleRouter` receives a `Network.dataMsg` event. This result needs to be integrated into the aggregate values being computed locally. If the result corresponds to an aggregate query, that result is forwarded into the `AggOperator` component, otherwise it is simply forwarded up the routing tree towards the root.

#### 5.2.2 SelOperator

The `SelOperator` is responsible for relational *selection*: testing whether tuples match predicates (in task `doFilter`). Currently, the only expressions supported are standard arithmetic comparisons of attributes with constants.

#### 5.2.3 AggOperator

This component performs two SQL features: `GROUP BY` and aggregation.

The optional `GROUP BY` feature partitions the data by the value of a (set of) attribute(s). Aggregate functions are computed for each partition, over any attributes *not* in the `GROUP BY` clause. In the absence of a `GROUP BY` expression, the aggregate is computed over all tuples. As described in Section 3, aggregate results are updated once per “epoch”.

The code in this component needs to (a) take readings from the current node (`Operator.processTuple`), (b) merge those readings with sub-aggregates from the subtree (`Operator.processPartialResult`), and (c) return this node’s sub-aggregate results up the tree (`Operator.nextResult`). It also manages allocating aggregation state for each group using the `TinyAlloc` component (Section 5.3), and provides a utility to reset the running aggregation state (`Operator.resetExprState`).

### 5.3 TinyAlloc: The TinyDB Memory Manager

This component, being very general-purpose, is located in `tinyos-1.x/tos/shared/TinyAlloc.{c,comp}` for use by other applications.

`TinyAlloc` is a simple, handle-based compacting memory manager. It allocates bytes from a fixed size frame and returns handles (pointers to pointers) into that frame. Because it uses handles, `TinyAlloc` can move memory around in the frame without changing all the external references. Moving memory is a good thing because it allows frame compacting and tends to reduce wasted space. Handles can be accessed via a double dereference (`**`), and a single dereference can be used wherever a pointer is needed, but if a single dereference is to be stored, the handle must be locked first (via `MemAlloc.lock(h)`), as otherwise `TinyAlloc` may move the handle and make the reference invalid.

**BEWARE:** Passing around dereferenced handles without locking is a common source of bugs, as are problems that result from memory not being unlocked.

Like all good TinyOS programs, TinyAlloc is split-phase with respect to allocation and compaction. Allocation/reallocation completion is signalled via a `MemAlloc.allocComplete()` signal and compaction via a `MemAlloc.compactComplete()` signal. All other operations complete and return in a single phase. Note that compaction may be triggered automatically from allocation; in this case a `compactComplete` event is not generated.

Handles are laid out in the frame as follows:

```
[LOCKED] [SIZE] [user data]
```

Where:

```
LOCKED      : a single bit indicating if the handle is locked
SIZE        : 7 bits representing the size of the handle
user data   : user-requested number of bytes (**h) points to
               [user data], not [LOCKED].
```

Calling `MemAlloc.size(h)` returns the size of `[user data]` (note that the internal function `size()` returns the size of the entire handle, including the header byte.)

## 5.4 TinyDB Network Topology Manager

The **Network** component handles all the mote-to-mote and mote-to-serial-port communication for TinyDB, routing *query* and *data* messages. In doing so, it also participates in a distributed algorithm for network topology layout. Messages are all of type `TOS_Msg`, and begin with a `DBMsgHdr` structure (see `tinynos-1.x/tos/include/TinyDB.h`), followed by a payload.

### Topology Maintenance

Most of the code in this component manages the network topology. The network topology is maintained as a routing *tree*, with Mote #0 at the root. As a rule, query messages flood down the tree in a straightforward fashion. Data messages flow back up the tree, participating in more complex query processing algorithms. Mote #0 passes result data to the front-end code via its serial interface. The only exception to “query-down/data-up” rule is that the root itself sends out periodic (empty) data messages as a “heartbeat”, so that its communication abilities can continue to be measured while a query runs.

By default, a simple tree-maintenance algorithm is used. This algorithm has each mote keep track of a list of other motes from which it receives messages (*neighbors*). Among these neighbors, it chooses the best one as its *parent* in the tree. Alternatively (for testing purposes) the network can be forced to choose a static topology based on the numbering of the nodes. This is done via the `forceTopology()` command.

### Message Handling

Upon receiving a message on the network, this component invokes the internal routine `processHeader`, which examines the header of each packet received on the radio. This code drives much of the logic in the component. It first updates statistics that are maintained for the parent-choice logic, and updates



its choice of parent if necessary. Then, if the message is a data message destined for another node, it drops the message. Otherwise, it handles the message accordingly.

## 5.5 TinyOS Service Components

We describe these TinyOS services only briefly. For more detail see TinyOS.

- **Clock:** Provides a system clock, and clock interrupts.
- **GenericComm:** A generic communications layer, supporting radio and serial communication.
- **Leds:** Control of the LED indicators on the motes.
- **Main:** A shell to initialize subordinate modules, and start them up.
- **Pot:** Get and set the level of the potentiometer (transmission-power controller) on the radio.
- **RandomLFSR:** A psuedo-random number generator, based on a 16-bit Linear Feedback Shift Register.
- **Reset:** Reset a mote (equivalent to toggling the power switch.)
- **Timer:** A service for setting (multiple) timers to generate subsequent interrupts.

## 5.6 Attributes: Sensor Components and Introspection

We describe these TinyOS services only briefly. For more detail see TinyOS.

- **Accel:** Accelerometer: measures movement in two dimensions (X and Y).
- **Mag:** Magnetometer: measures magnetic field.
- **Photo:** Light sensor.
- **Temp:** Thermometer: measures temperature.
- **Voltage:** Measures remaining voltage in the battery.

## 6 Using the TinyDB GUI with PostgreSQL

TinyDB includes a simple facility to log results of queries to a PostgreSQL database. Postgres is an open-source, widely used DBMS available on a wide-variety of platforms ( See [www.us.postgresql.org](http://www.us.postgresql.org) for more information.) To enable logging to a Postgres database, set up Postgres according to the directions in the next section, and then enable the “Log to Database” option when inputting a query via the query GUI (see Figure 2.) Note that it is not neccessary to configure Postgres *unless you wish to use the logging facilities*. The results of the query will be written to a table named “qn”, where *n* is a unique sequence number assigned to the query. You can determine the current sequence number for a query by calling the `getTableNames()` method on the `DBLogger` object used to initiate query

logging. The resulting table will contain a timestamped entry for each result returned by the query. For example, if your query is *select light,temp from sensors*, the resulting Postgres table will have the schema:

result_time:timestamp	epoch:integer	light:integer	temp:integer
-----------------------	---------------	---------------	--------------

In this way, TinyDB query results can be accessed offline and joined with results from other static, offline data sources.

## 6.1 Configuring PostgreSQL

The following is a simple guide for installing and configuring Postgres to support logging of TinyDB queries. We have successfully used TinyDB with Redhat Linux 7.2 and 7.3 and Cygwin; other Linux distributions should be straightforward to configure.

1. **Download and Install PostgreSQL** *Note that Cygwin comes with a default installation of Postgres, so this step is not necessary under Cygwin.*

Download Postgres for your distribution from

<http://www.ca.postgresql.org/ftp/site/binary/v7.2.1/RPMS/>. You'll need at least the following packages:

```
postgresql-libs
postgresql
postgresql-server
postgresql-jdbc
```

Install the packages in the above order, and then start the Postgres service. Under Redhat, the command to do this is: `/etc/rc.d/init.d/postgresql start`

2. **Enable Remote Connections**

You'll need to modify your Postgres installation to allow connections over TCP/IP sockets. With the Redhat RPMS, Postgres is configured to store its data files in `/var/lib/pgsql/data`; you'll need to substitute appropriately in the commands below if your Postgres files are in a different location:

- `cd /var/lib/pgsql/data`
- Edit `postgresql.conf` by replacing the line (at the end of the comments section) that reads:  
`#tcpip_socket = false`  
with  
`tcp_socket = true`
- Restart the postgresql server (under Redhat, type `/etc/rc.d/init.d/postgresql restart`)

### 3. Install the PostgreSQL JDBC driver

Next, you'll need to make sure the Postgres JDBC driver (included in the TinyOS distribution) is in your classpath. The jar is located at `tinyos-1.x/tools/java/jars/pgjdbc2.jar`; under bash, you would type:

```
export CLASSPATH=$CLASSPATH:tinyos-1.x/tools/java/jars/pgjdbc2.jar
```

### 4. Create the TinyDB User and Database

The TinyDB config file (see 3.5) above specifies a database and user name to use when accessing Postgres. Both need to be created before TinyDB will work; to do this under Redhat, type:

```
su
postgres
createdb tinydb
createuser tele
```

### 5. Create the Queries Table

TinyDB logs all of the queries that are logged to a table “queries”, which contains the name of the result table for the query, time the query was posed, and the text of the query. You must create this table before TinyDB; to do so under Redhat, do the following:

- `su; su postgres`
- Get a Postgres command prompt by typing: `psql tinydb`
- Create the table by typing: `create table queries (query_table varchar(10), query_time timestamp, query_string varchar(500));`

## 7 Frequently Asked Questions

- **I'm using a Serial Forwarder and TinyDBMain complains that it can't connect to the network when I try to start it. Why doesn't it find my Serial Forwarder?**

TinyDB is configured to start its own Serial Forwarder by default. You can make it use an existing serial forwarder by changing the value of the `start-sf` flag in the `tinydb.conf` file (see Section 3.5) to `false`. You'll need to specify the port number and host name of your own Serial Forwarder as well.

- **I've installed TinyDB on my motes and connected them to the basestation, but I can't ever seem to get them to send or process queries. What's going on?**

First (as always), check that all your cables are properly connected. Power cycle your base station. If you still can't send queries, verify that the `am-group-id` field in the `tinydb.conf` file (see Section 3.5) has the same value as the `DEFAULT_LOCAL_GROUP` variable set at the beginning of the `tinyos-1.x/apps/Makeinclude` file.

- **I send a query into the network. I get results back for a short period of time, but then stop receiving any results. The motes are all blinking their red and green LEDs like crazy. What's going on?**

You're probably running a query with a fast epoch duration. The basestation periodically broadcasts heartbeats that tell the motes it's still alive, but the motes can lose track of the basestation if they are sending data very fast. You can work around this problem by using the "Change Base Bcast Interval" button on the TinyDB command window just after injecting the query.

- **I think I've found a bug in TinyDB. What should I do?** There is a bug tracker for TinyDB in the TinyOS sourceforge project, under "Trackers". Check out the URL:

[http://sourceforge.net/tracker/?atid=494883&group\\_id=28656&func=browse](http://sourceforge.net/tracker/?atid=494883&group_id=28656&func=browse)

for a list of bugs that have been submitted. If you see a similar bug there, we may have posted a workaround. If your bug isn't there, or the workaround is not satisfactory, feel free to enter a new bug or send us a bug report and we'll enter it for you!

## 8 Version History and Author Information

This document was written by Joe Hellerstein, Sam Madden, and Wei Hong. This is Version 0.3, last updated October 15, 2002 by Sam Madden.

## A TinyDB Source Files

The following files in the TinyOS CVS tree are a part of the TinyDB distribution:

- `tinyos-1.x/tos/lib/TinyDB`
  - `/AggOperator.rd`
  - `/DBBufferC.nc`
  - `/DBBuffer.nc`
  - `/DBBuffer.h`
  - `/ExprEvalC.nc`
  - `/ExprEval.nc`
  - `/NetworkC.nc`
  - `/Network.nc`
  - `/Operator.nc`
  - `/ParsedQueryIntf.nc`
  - `/ParsedQuery.nc`
  - `/QueryIntf.nc`
  - `/Query.nc`
  - `/RadioQueue.nc`
  - `/SelOperator.nc`
  - `/TinyDBAttr.nc`

- /TinyDBCommand.nc
  - /TinyDB.h
  - /TupleIntf.nc
  - /TupleRouter.nc
  - /TupleRouterM.nc
  - /Tuple.nc
- tinyos-1.x/tos/interfaces
  - /Attr.h
  - /AttrRegisterConst.nc
  - /AttrRegister.nc
  - /AttrUse.nc
  - /Command.h
  - /CommandRegister.nc
  - /CommnadUse.nc
  - /MemAlloc.nc
  - /SchemaType.h
- tinyos-1.x/tos/lib
  - /Command.nc
  - /Attr.nc
  - /TinyAlloc.nc
- tinyos-1.x/tools/java/net/tinyos/tinydb
  - AggExpr.java
  - AggOp.java
  - Catalog.java
  - CmdFrame.java
  - CommandMsgs.java
  - MagnetFrame.java
  - QueryExpr.java
  - QueryField.java
  - QueryListener.java
  - QueryResult.java
  - ResultFrame.java
  - ResultGraph.java
  - ResultListener.java
  - SelExpr.java
  - SelOp.java
  - TinyDBCmd.java
  - TinyDBMain.java
  - TinyDBNetwork.java

- TinyDBQuery.java
  - Makefile
  - parser/
    - \* Makefile
    - \* senseParser.{cup,lex}
- tinyos-1.x/apps/TinyDBApp
  - Makefile
  - TinyDBApp.nc

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## Glossary

**Ptolemy** Ptolemy is a simulation project at UC Berkeley. The TinyDB application borrows a small piece of code from Ptolemy for plotting results.

**Active Messages (AM)** A networking protocol developed at UC Berkeley, used for very-low-latency dispatch of incoming messages. It provides an asynchronous (sometimes called “split-phase”) programming model.

**Aggregation** Aggregation is the process of bringing together multiple data objects. In SQL, it typically denotes the summarization of multiple numeric values with a single summary statistic, like COUNT, AVERAGE, MAX or MIN.

**API** Application Programming Interface. A set of interfaces provided by a subsystem that enable programmers to use the subsystem in their own applications.

**Attribute** In traditional databases, a row in a table, consisting of a name and a data type. In TinyDB, an attribute often corresponds to a physical sensor reading like light, temperature, etc. However, the system can support attributes provided in software as well, like NodeID, network parent, and so on.

**Catalog** A set of metadata describing a database, including the schema, and whatever other metadata the system provides.

**Client** In the TinyDB context, a piece of code running on a PC that invokes the TinyDB Java API. Synonym for Front-End.

**Column** See Attribute.

**COM1** The name of the standard serial port on a PC.

**Component** A basic building block in a TinyOS program. See the TinyOS documentation for details on the TinyOS programming model.

**Declarative Language** A language in which you express what you desire, without detail on how to achieve it. Declarative languages are popular in database systems; SQL is (largely) declarative. Declarative languages are useful for providing a very deep level of indirection between application requests and system implementation of the requests – this is especially important if the system’s optimal implementation could change frequently (as in a sensor network, which is quite unpredictable).

**Download** In the context of TinyOS/TinyDB, this is the process of transferring a compiled code image onto a mote.

**Embedded C** A program written in C that runs autonomously on a small device like a mote.

**Epoch** A discrete window of time. In TinyDB's SQL, new answers to a query are produced every epoch, and the duration of an epoch can be specified in the query.

**Expression** A simple interpretable clause in a query, like an arithmetic comparison (e.g. `light > 80`), or an aggregate function (e.g. `AVERAGE(temp)`)

**Filter** A predicate that may remove some readings from the query. Synonym for Selection.

**Front-End** In the TinyDB context, a piece of code running on a PC that invokes the TinyDB Java API. Synonym for Client.

**Group By** In SQL, an expression that partitions the set of tuples that satisfy a query, to prepare for computation of an aggregate per partition. Typically the Group By expression is simply an attribute name, e.g. `GROUP BY temp`; tuples are partitioned by the value of the attribute.

**GUI** Graphical User Interface.

**Handle** A pointer to a pointer to an object. The double level of indirection allows the objects to be relocated without informing the code that manipulates the handles.

**Heartbeat** A periodic network message that simply indicates that the sender is active and connected.

**In-Network** A description for algorithms that run in intermediate network devices in a multi-hop network, rather than the hosts at the endpoints.

**Listener** A Java object that responds to certain kinds of events.

**Mote (Berkeley Mote)** A wireless sensor network node, developed at UC Berkeley. A mote is a device combining a small microprocessor, one or more sensors, and a radio. The name "mote" comes from the "Smart Dust" metaphor introduced by sci-fi author Neal Stephenson.

**Multi-Hop** A scenario in which network messages visit multiple routers between source and destination.

**Neighbor** Two network nodes are neighbors if they can communicate directly, without involving any intermediate routing.

**Node** In this context, a compute device in a network; typically a mote in a sensor network.

**Object-Relational** A database model developed in the Postgres project at UC Berkeley, which extends the relational model with object-oriented features like extensible abstract data types, including OO methods that are executed by the database engine (rather than at a client).

**Parent** In a TinyDB routing tree, the parent of node  $n$  is the node that listens to  $n$ 's data messages.

**Predicate** A boolean expression.

**Processed** In the TinyDB API, a result tuple is considered “processed” when all the attributes have been concatenated together with fully aggregated values.

**Query Plan** An interpretable description for executing a query, typically consisting of a few high-level operators connected in a dataflow tree.

**Query Processor** A system for executing queries.

**Relational Model, Relational Languages** Invented by Turing Award-Winner Ted Codd, the relational data model is the most prevalent representation for data today. It is extremely simple, representing all information as relations (“tables”) consisting of tuples (“rows”) made up of well-typed attributes (“columns”). A relational query language is one that can express a subset of 1st-order logic over relations. The standard relational query language is SQL.

**Root** In TinyDB, this refers to the root of the routing tree, which is a sensor that is connected to the serial port of the PC running the front-end code.

**Routing** The process of moving data through a multi-hop network from source to destination. In TinyDB, the dataflow involved in routing interacts significantly with the dataflow involved in query processing.

**Row** See Tuple.

**Sample** In the sensor context, this often refers to a single discrete reading taken by a sensor. It is called a sample to highlight the approximate nature of representing a continuous, real-world process as a stream of discrete digital readings.

**Schema** A metadata description of a relation or set of relations. A simple schema includes the name of the relation(s), the names and data types of the attributes in the relation, and the default order of the attributes. Note that the schema describes what data *can* exist in the relation, not what *currently* exists.

**Selection** In relational languages, the operation of choosing those tuples in a relation that match some predicate. See Filter.

**Semantics** The meaning of a construct.

**Sensor** A device for converting physical phenomena into electronic signals. In this document we sometimes use the word sensor interchangeably with the word mote: the combination of a sensor, a processor, and a radio.

**Sensor Network** A network – often a wireless network – in which the nodes are devices like motes that combine sensors with processing and communication.

**Serial Port** An I/O port present on most PCs.

**SQL** The Structured Query Language, a standard language used for specifying queries to relational databases.

**Table** See Relation.

**Timeslot** An assigned range of time. In order to avoid network congestion, some protocols explicitly allocate timeslots across potential senders so that their messages do not collide.

**TinyDB** A system for declaring and executing queries in a wireless sensor network.

**TinyOS** A set of C-based low-level libraries for writing embedded systems on the Berkeley Motes. Key features of TinyOS include hardware abstractions for the Berkeley motes, an Active Messages-based communication layer for both radio and serial communication, and a programming model that supports both procedure calls and asynchronous event programming.

**Topology** In our discussion, the directed graph that represents the communication pattern between motes in a wireless network.

**Tuple** A list of attribute-value pairs that corresponds to the schema of some relation.